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PRINCIPAL INVESTIGATOR
Name: Jane Lee Fox
SS: #[redacted]
Title: Associate Professor
Dept.: Institute for Terrestrial and Planetary Atmospheres
Telephone: (516) 632-8317

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Abstract

We have begun our studies of Titan and Triton by setting up a coupled ion and neutral chemical model of the ionosphere and thermosphere of Titan. The chemical scheme employs over 100 reactions and 46 species. Transport by diffusion and eddy diffusion of neutrals is included along with ambipolar diffusion of ions. We have computed the photoionization, photodissociation, electron impact excitation and ionization rates for the most important species, and the densities of ions and neutrals for a dayside model. We have computed the heating rates as a function of altitude and the heating efficiencies. We find that the heating efficiency in our standard model varies from about 30% near 800 km to 22% near 2000 km. We report here also on some photoelectron impact excitation rates for band systems of N_2 in the Titan atmosphere. In the future, we propose to polish and publish our model, extend it to Triton, and look into excitation and emission of the N_2 and N_2^+ band systems.

Progress Report

In the last year, Roger Yelle and I have modeled the thermosphere and ionosphere of Titan, with a view toward determining the ionospheric structure, altitude profiles of minor neutral species, and the EUV heating efficiencies. Heating efficiencies are important in determining the neutral temperature structure and thus the chemical structure of the thermosphere. The ionospheric and neutral structures are important for computing the airglow intensities. Our neutral model includes the N_2 and CH_4 density profiles from Voyager solar occultation data [Smith et al., 1982]; we adopted the densities of ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2) from the photochemical calculations of Yung et al. [1984]. The initial neutral atmosphere is shown in Figure 1. Our chemical scheme has included 108 reactions, 24 neutral species and 22 ions. The neutral species that are computed in the model are H, H_2, C, CH, $^3CH_2$, $^1CH_2$, CH_3, C_2, C_2H, C_2H_3, C_2H_5, N, $N(^2D)$, NH, CN, HCN, H_2CN, CHCN, HC_3N, C_2N, HC_2N_2, C_3N, H_2C_3N, and C_4N_2. The ions include H^+, H_2^+, H_3^+, C^+, CH^+, CH_3^+, CH_4^+, CH_5^+, $C_2H_2^+$, $C_2H_3^+$, $C_2H_4^+$, $C_2H_5^+$, N^+, HCN^+, H_2CN^+, N_2^+, N_2H^+, C_2^+, C_2H^+, $C_2H_6^+$ and a pseudo-ion that represents all other hydrocarbon ions, $C_xH_y^+$. The ion-molecule reactions were taken from the compilations of Anicich and Huntress [1986], Ikezoe et al. [1986], and more recent references. The rate coefficients for the dissociative recombination reactions have been fully updated. The calculation includes diffusion and eddy diffusion of neutrals and ambipolar diffusion of ions. Before we submit these results for publication, probably this September or October, we will expand the ion list to include NH^+, NH_2^+, NH_3^+ and NH_4^+.

We have adopted the F79050N solar fluxes of Hinteregger [private communication; see also Torr et al., 1979], which is appropriate to a period of high solar activity, such as that which prevailed at the time of the Voyager 1 and 2 encounters with Saturn and Titan (1980–1981). The solar zenith angle in our model is 60°. Photoionization and photodissociation are included for N_2, CH_4, C_2H_6, C_2H_4, C_2H_2, and H_2, as well as photoionization of H, N and C. In addition, photoionization of CH_3 by Lyman alpha, and photodissociation of HCN are also included. Electron impact excitation and ionization are included for N_2, CH_4, H_2, H, C and N. The cross sections for photoionization and dissociative photoionization of N_2 from threshold to 116 Å were taken from Samson et al. [1987]. The N_2 electron impact cross sections are the same as those adopted by Fox and Victor [1988] in their study of electron energy deposition in N_2 gas. The cross sections for photoionization of hydrocarbons, and electron impact on H_2, H and CH_4 are the same as those compiled by Kim and Fox [1990]. The cross sections for photodissociation of HCN were taken from Nuth and Glicker [1982] and Lee [1980]. The cross sections for photoionization of C and N were taken from LeDourneuf et al. [1976], Cantu et al., [1981], and Daltabuit and Cox [1972]. The electron impact ionization cross sections for C and N were adopted from the measurements of Brook et al. [1978]. The ionization potential of CH_3 is 9.84 eV, and photoionization by solar Lyman alpha is possible, but the cross section has not been computed or measured. We assume, as did Strobel [1975], that the cross section is equal to that of atomic carbon at threshold, 1.2×10^{-17}cm^2.

Ion Production Rates. Altitude profiles of the production rates of the six major ions are shown in Figure 2. N_2 is the major ion produced below about 1650 km, and CH_4^+ is the major ion produced above that altitude. At the ion peak, N^+ is the second most important ion produced, largely as a result of dissociative ionization of N_2. Below

about 950 km, $C_2H_4^+$ is the second most important ion produced. Its major source is photoionization of C_2H_4. CH_3^+ is produced by photodissociative ionization of CH_4, C_2H_4, and C_2H_6, electron impact dissociative ionization of CH_4, and photoionization of CH_3 by Lyman alpha. The most important source of CH_3^+ is photodissociative ionization of CH_4, with a column integrated rate of $3.1 \times 10^7 cm^{-2}s^{-1}$, but photoionization of CH_3 by Lyman alpha is comparable, with an integrated rate of $1.6 \times 10^7 cm^{-2}s^{-1}$.

Because N_2 has a very high ionization potential (15.58 eV) (as shown in Table 1), the ion will react to produce ions whose parent neutrals have lower ionization potentials. Thus we do not expect or observe N_2^+ to be the terminal ion. N_2^+ reacts rapidly with methane,

$$N_2^+ + CH_4 \rightarrow CH_3^+ + N_2 + H$$

$$N_2^+ + CH_4 \rightarrow CH_2^+ + N_2 + H_2$$

with acetylene,

$$N_2^+ + C_2H_2 \rightarrow C_2H_2^+ + N_2$$

and with H_2

$$N_2^+ + H_2 \rightarrow N_2H^+ + H.$$

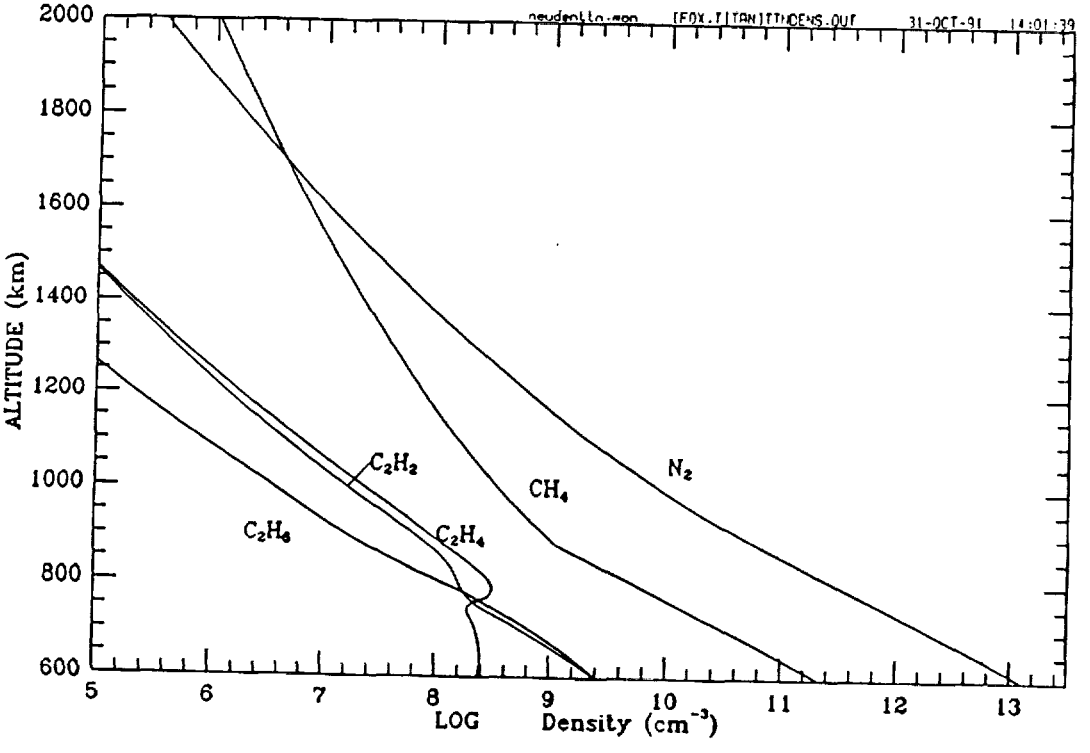

Figure 1. Neutral atmospheric model of Titan that is employed in the calculations.

The product ions then react further, transforming the ionosphere to that shown in Figure 3. In our model H_2CN^+ is the major ion below about 1200 km; CH_5^+ is more important at higher altitudes. This is in contrast to the model of Ip [1990], in which N_2^+ was the dominant ion above 1400-1500 km. The source of the discrepancy is not obvious, but we believe our model to be superior to that of Ip, which is a photochemical equilibrium model and contains some outdated rate coefficients. The major source of H_2CN^+ at the ion peak is the proton transfer reaction

$$C_2H_5^+ + HCN \rightarrow H_2CN^+ + C_2H_4.$$

The analogous reaction of $C_2H_3^+$ is the also important.

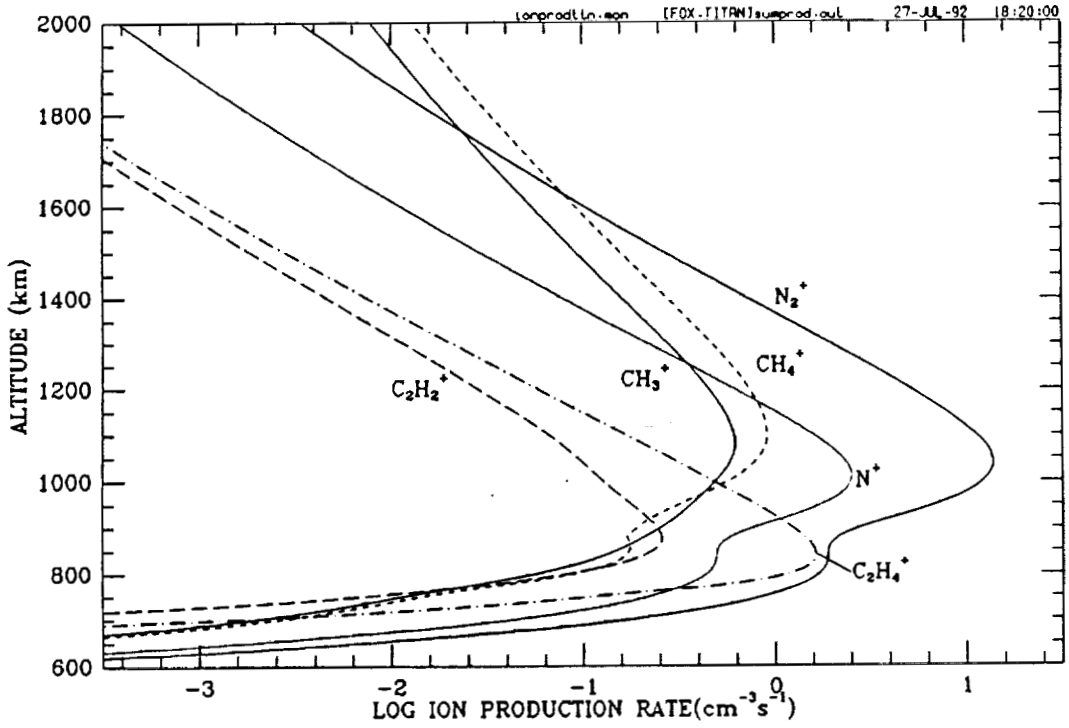

Figure 2. Altitude profiles of the production rates of the most important ions in the Titan ionosphere.

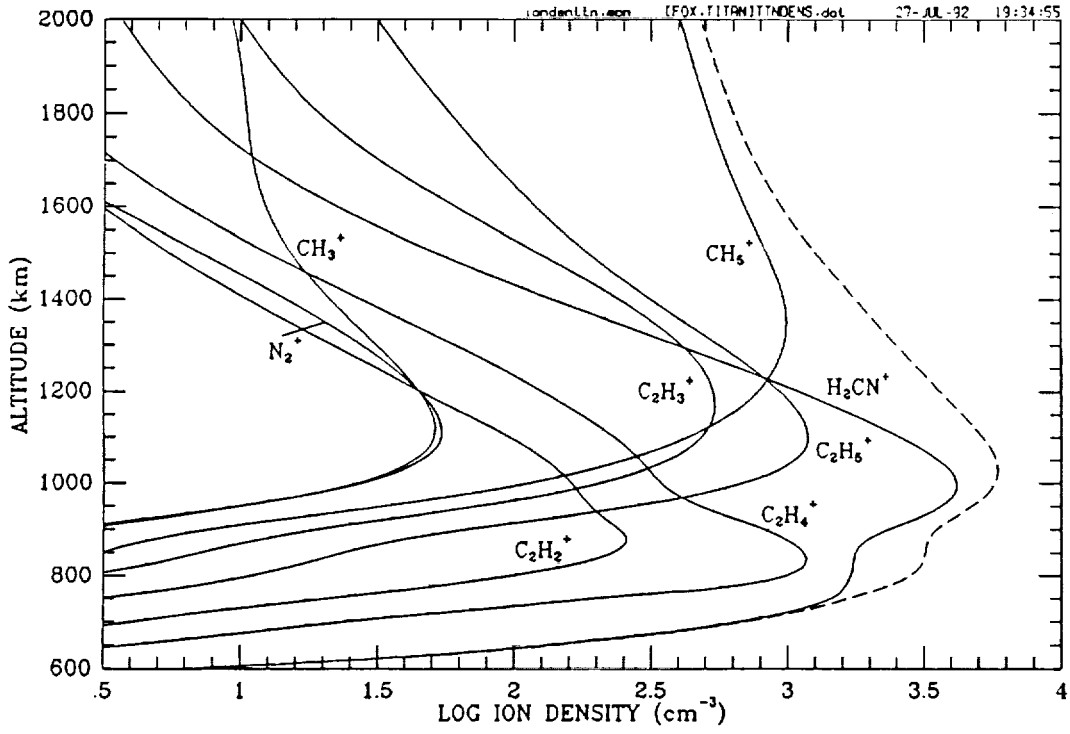

Figure 3. Altitude profiles of the densities of the most important ions in the Titan ionosphere.

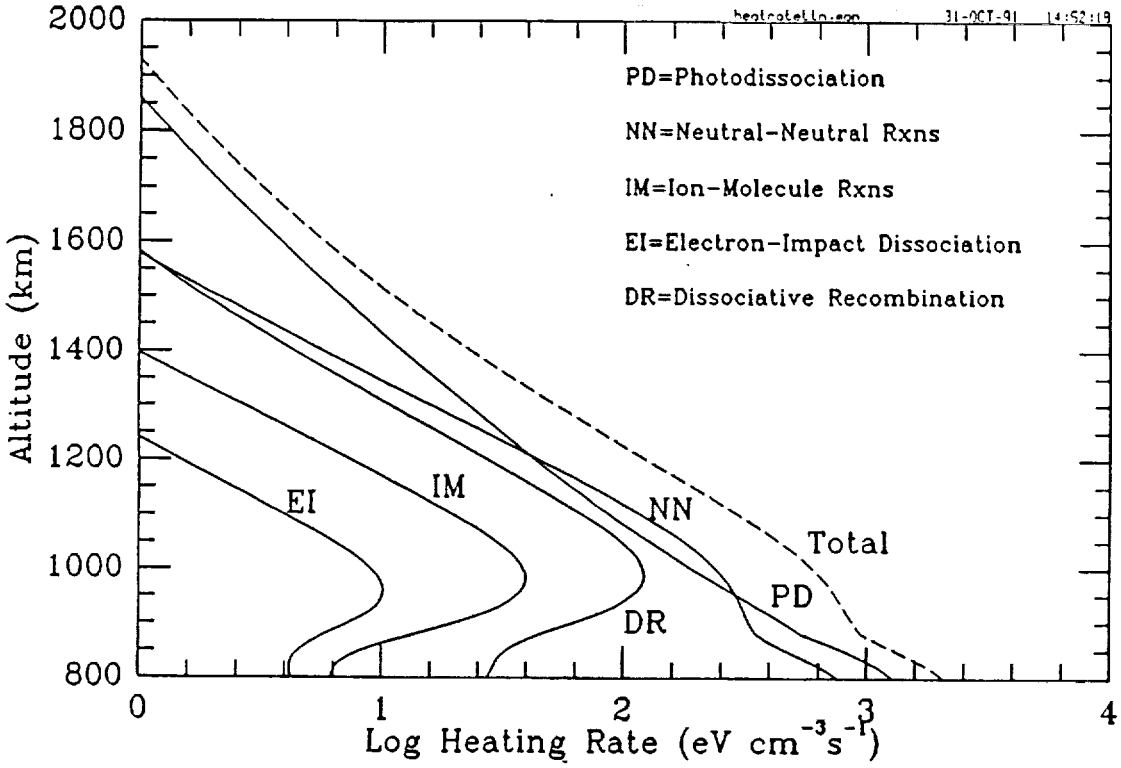

Figure 4. Altitude profiles of the heating rates of the most important processes in the Titan thermosphere.

EUV Heating Efficiencies.

The heating efficiency is the fraction of solar energy absorbed that is deposited locally as heat. The EUV (~100-1000 Å) and FUV (~1000–2000Å) regions of solar spectrum are absorbed in the thermospheres of planets. Solar energy is transformed to heat in photodissociation and photoelectron impact dissociation of molecules, in exothermic reactions, including ion-molecule reactions, neutral-neutral reactions, and dissociative recombination of ions with electrons.

In photodissociation, the amount of energy that goes into kinetic energy is the difference between the energy of the photon and the dissociation energy (which may include some internal excitation of the fragments). In the absence of information about the electronic states of the fragments, they are assumed to be produced in their ground states. When there are molecular products, some of the energy may be taken up as vibrational energy of the fragments. The energy that appears as vibrational excitation in photodissociation has been found to be small [cf. Fox, 1988 and references therein]; this would be expected to be especially true when the fragments are H atoms. We assume here that 25% of the excess energy appears as vibrational energy of molecular products, and the remainder is converted to kinetic energy, as we have in previous calculations of heating efficiencies [e.g. Fox, 1988]. A half-collision model suggests, however, that when one of the fragments is very light, such as a hydrogen atom or molecule, the energy that appears as vibrational excitation of the other fragment may be very small. For our final calculation, we will probably assume that only 10-15% of the energy is taken up as vibrational excitation in photodissociation.

Although N_2 is the major species in the atmosphere, its dissociation threshold is large, 9.76 eV, and, because most of the dissociation occurs through discrete excitation into predissociating states in the singlet manifold, it doesn't absorb longward of 985 Å. The peak heating rate due to photodissociation of N_2 is only 5.7 $eVcm^{-3}s^{-1}$ at about 1060 km, near the ionospheric peak. CH_4 is a strong absorber, and photodissociation of CH_4 is the most important heating process of this type. The peak heating rate is about $1.4 \times 10^3 eVcm^{-3}s^{-1}$ at 770 km. Although at this altitude infrared heating is more important than solar heating, the dominance of heating due to methane photodissociation extends to higher altitudes. At 1060 km, the heating rate due to methane photodissociation is 1.23×10^2 $eVcm^{-3}s^{-1}$. Even HCN photodissociation is more important than that of N_2, with a heating rate of about 8 $eVcm^{-3}s^{-1}$ at 1060 km.

The energy released in exothermic reactions can appear as kinetic energy of the products, thus resulting in heating. Dissociative recombination reactions in particular are often very exothermic and contribute significantly to heating. On Mars and Venus, dissociative recombination of the major ion, O_2^+, is the most important chemical heat source for the neutrals [Fox and Dalgarno, 1979, 1981; Fox, 1988]. On the Earth, dissociative recombination of NO^+ is the most important heat source of ground state reactions [Torr et al., 1980]. On Titan, we find that dissociative recombination is not as important as it is on the terrestrial planets, partly because the ions are "processed" more, that is, they have undergone more transformations before they recombine. More important, however, is the presence of methane, which is a strong absorber, increasing both the heating rate due to photodissociation and the production rate of neutral fragments that can participate in neutral-neutral reactions compared to the terrestrial planets.

In dissociative recombination of polyatomic molecular ions, as in photodissociation, some uncertainty exists about how much of the exothermicity appears as vibrational excitation of the molecular products. And just as for photodissociation, a half-collision model suggests that little energy is expected to be deposited as vibrational excitation. Although we have assumed that 25% of the energy released appears as vibrational energy of molecular fragments, we may reduce that number for the final calculation. The most important dissociative recombination reaction for neutral heating is that is of major ion, H_2CN^+, which actually has the structure $HCNH^+$. There are four exothermic product channels for this reaction:

$$\begin{aligned} HCNH^+ + e &\rightarrow HCN + H \\ &\rightarrow HNC + H \\ &\rightarrow CH_2 + N \\ &\rightarrow H_2 + CN. \end{aligned}$$

The only information that is available about the product channels is the measurement of Adams et al. [1991], that indicated that 0.63 H atoms are produced per recombination. This implies that the sum of the branching ratios for the first two channels is 63% and the sum of the second two branching ratios is 37%. We somewhat arbitrarily assume that production of HCN, the more stable isomer, is the dominant channel of the first two, and that the third channel is more important than the fourth.

In electron impact dissociation some of the energy lost by the electron may appear as kinetic energy of the neutrals produced. In general, the fraction of energy that appears as kinetic energy is not constant for a given process and it is therefore not possible to determine the heating due to electron impact dissociation exactly. An average value may be determined from time-of-flight studies, or derived from electron energy loss spectroscopy, but measurements are not available for all of the electron impact dissociations. Fortunately, Prokop and Zipf [1982] have measured the average kinetic energy of the N atoms that are released in electron impact dissociation and dissociative ionization of N_2, and report values of 0.45 eV and 3.0 eV, respectively. Since this is the most important species in the Titan atmosphere, it accounts for a most of of the electron energy loss at the ion peak, near 1000 km. In computing the heating due to electron impact dissociation, we have adopted the measured values for N_2, and we have assumed a value of 1.0 eV per dissociation or dissociative ionization of H_2 and CH_4.

In ion-molecule and neutral-neutral reactions, the exothermicity can appear as internal energy of the products, as well as kinetic energy. In general, little information is available about the partitioning of energy among the various modes. For our standard calculation, we have assumed that 60% of the energy appears as vibrational energy of the products. We also then compute lower and upper limits to the heating efficiency using the values 80 and 40%, respectively. For ion-molecules reactions, the partitioning of kinetic energy between the the neutral and the ion product is determined by momentum conservation. The most important ion-molecules reactions for thermospheric heating are

$$N_2^+ + CH_4 \rightarrow CH_3^+ + N_2 + H$$

and

$$CH_3^+ + CH_4 \rightarrow C_2H_5^+ + H_2.$$

The most important neutral-neutral reactions are:

$$CH_2 + CH_2 \rightarrow C_2H_2 + H_2$$

and

$$NH + N \rightarrow N_2 + H.$$

The heating rates as a function of altitude are presented in Figure 4 and resulting heating efficiencies are shown in Figure 5. The standard values vary from about 30% at 800 km to 22% at 2000 km. The lower and upper limits are about smaller and larger by about 0.05 near 800 km and converge to nearly the standard value at 2000 km. These heating efficiencies are very different from those appropriate to Earth, which are in excess of 50%, and are more like those for Venus and Mars, which are about 20–24%. It is apparent that in N_2 atmospheres, it is the minor species that dominate the absorption and heating: O_2 for the terrestrial case, and methane for Titan.

Our major contribution at Stony Brook has been compiling the cross sections for photoprocesses and electron impact processes, calculation of the photoionization and photodissociation rates of the major and minor neutral species, calculation of the photoelectron impact production rates, as well as updating the tentative chemical reaction list provided by R. Yelle with more recent rate coefficients. Yelle wrote the chemistry code. We also computed the heating efficiencies from the ion and neutral reaction rate list provided by Yelle, added the heating due to photoelectron impact, photodissociation, and determined estimates for the amount of energy that goes into vibrational excitation of molecular products.

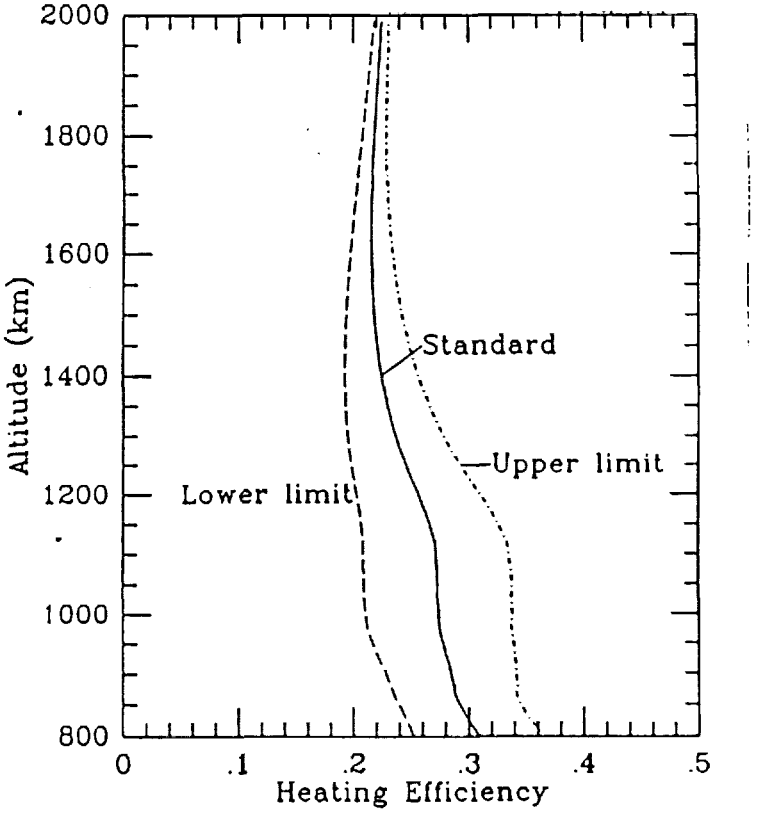

Figure 5. Altitude profiles for the heating efficiencies for solar radiation in the 14–2000Å interval. The standard, upper limit and lower limit profiles are illustrated.

Future Work

During the next year, we would first like to polish and publish our model of the Titan ionosphere-thermosphere, including the reactions of NH^+, NH_2^+, NH_3^+, and NH_4^+, and to do a literature search to be sure that we have included all relevant odd nitrogen reactions. Once we are confidant that our model is the best that we can construct, then we will move on to do more detailed dayglow calculations.

The ultraviolet spectrometers on Voyagers 1 and 2 measured emission from the Titan atmosphere in the range 500–1700 Å, and the spectrum was found to be dominated by emission of N_2 and N [Strobel and Shemansky, 1982]. The most intense features of N_2 were the $c_4'^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$ Rydberg bands, but the Birge-Hopfield ($b^1\Pi_u \rightarrow X^1\Sigma_g^+$) and Lyman-Birge-Hopfield ($a^1\Pi_g \rightarrow X^1\Sigma_g^+$) bands were also present in the spectrum. The former two band systems are dipole allowed, and could be excited by fluorescent scattering, but the predicted intensities are small [Strobel and Shemansky, 1982]. The emissions have been found to be brightest in the quadrant facing into the corotating magnetosphere of Saturn, and it has therefore been suggested that the emissions could be produced by impact of low energy electrons from Saturn's magnetosphere (Strobel and Shemansky, 1982). Other features identified include the 1134-, 1200- and 1243-Å lines of N and the 1085-Å line of N^+. Voyager 2 measured ultraviolet emissions from Neptune's satellite Triton. The spectra are similar. The strong emission at Lyman alpha in both spectra results from resonance scattering by thermospheric and exospheric atomic hydrogen.

We will first model the nitrogen band systems using only solar and photoelectron excitation. We have already done such calculations for the N_2 Vegard-Kaplan ($A^3\Sigma_u^+ \rightarrow X^1\Sigma_g^+$), second positive ($C^3\Pi_u \rightarrow B^3\Pi_g$), Lyman-Birge-Hopfield ($a^1\Pi_g \rightarrow X^1\Sigma_g^+$), first positive ($B^3\Pi_g \rightarrow A^3\Sigma_u^+$), reverse first positive, and $W^3\Delta_u \rightarrow B^3\Pi_g$ band systems on Venus and Mars [Fox et al., 1977; Fox and Dalgarno, 1979; 1981; Fox, 1992]. A product of the photoelectron energy deposition calculation is a determination of the integrated rates for production of the excited triplet and singlet states of N_2. The predicted column integrated rates for the triplet states and the $a^1\Pi_g$ state (the upper state of the Lyman-Birge-Hopfield band system) are shown below:

State	Integrated Production Rate ($10^6 cm^{-2}s^{-1}$)
$A^3\Sigma_u^+$	113
$B^3\Pi_g$	131
$W^3\Delta_u$	112
$C^3\Pi_u$	60
$B'^3\Sigma_u$	31
$a^1\Pi_g$	67

These calculations indicate that an ultraviolet spectrometer, with a channel in the near UV, would observed substantial intensities of the Vegard-Kaplan and second positive bands. Electron impact can account for about two-thirds of the measured Lyman-Birge-Hopfield bands, although absorption by methane will modify that number. We will modify existing codes to predict the intensities of the individual bands, including absorption.

Of the band systems arising from the states listed above, only the Lyman-Birge-Hopfield bands appear in the FUV. Also, the strong emission from the N_2 Rydberg bands that are seen in the Titan airglow is not observed on any of the terrestrial planets. This is because the c_4' state has a small but finite predissociation probability, which, in an optically thick situation, such as the Earth's thermosphere, leads ultimately to dissociation rather than to emission. Hence it has been inferred that the Rydberg bands must be produced at high altitudes on Titan [Strobel and Shemansky, 1982; Conway, 1983]. More information is available now about the cross sections for electron impact excitation of N_2 band systems [e.g., Ajello et al., 1989; James et al.,1990; Tripp et al., 1990]. In addition, the cross sections used by Strobel and Shemansky [1982] have been revised downward by a change in the calibration standard by Shemansky et al. [1985] and Woolsey et al. [1986].

The N_2^+ Meinel and first negative bands may be produced by photoionization, electron impact ionization, and fluorescent scattering of radiation. N_2^+ is probably vibrationally excited at high altitudes in the ionospheres of Titan and Triton. We will model the N_2^+ vibrational distribution, just as we and others have done for Earth [Broadfoot et al., 1967, 1971; Degen, 1977, 1981; Fox and Dalgarno, 1985], Mars [Fox and Dalgarno, 1983] and Venus [Fox, unpublished calculation; see Fox, 1991]. The vibrational distribution can be important for modeling the chemical and thermal structure, as well as determining the intensities of N_2^+ emissions. Noren et al. [1989] have recently suggested that rate coefficients for dissociative recombination of ground state N_2^+ is a factor of five slower than that of excited states, although this contradicts the more recent calculations of Guberman [1991]. Guberman did point out, however, that the yield of $N(^2D)$ may vary dramatically with vibrational excitation. In order to model the high altitude ion distributions or the yields of metastable N atoms, it is necessary to know the vibrational distribution of N_2^+. Loss of the ion will be via dissociative recombination in the upper part of the ionosphere. In the lower ionosphere charge transfer or atom/ion interchange reactions with neutral species may dominate, and the rates of those reactions can also depend on the vibrational level of the ion. For example, if the Ar densities are significant (1–2% or more) a major production reaction for Ar^+ should be charge transfer from vibrationally excited N_2^+, just as we have found for the terrestrial ionosphere [Fox, 1986] and for Mars [Fox, unpublished calculations].

In the ionospheres of the terrestrial planets, fluorescent scattering of solar radiation in the N_2^+ Meinel and first negative band systems is the dominant factor in producing a non-LTE vibrational distribution for N_2^+[Broadfoot, 1967; Degen, 1977; Fox and Dalgarno, 1983; 1985] On Titan, fluorescent scattering will also be important, but we expect that at times when the atmosphere of Titan is within Saturn's magnetosphere (or interacts directly with the solar wind), electron induced fluorescence will also play a major role, as Degen [1981] showed for terrestrial aurorae. Because of the high ionization potential of N_2, chemical reactions are not likely to play a major role in producing vibrationally excited N_2^+. Nor do we expect collisional excitation to be as important in producing vibrationally excited N_2^+ as it is in the ionospheres of the terrestrial planets, mostly because the temperatures are lower. Strictly speaking, however, it is the ion temperature that is important in determining collisional excitation rates and although the neutral temperatures are low, the ion temperatures may not be. A Nagy [private communication] is computing the ion temperatures on Titan, so those numbers should be available soon. We also expect

the N_2^+ at the peak on Titan to be more vibrationally excited than at the F_1 peak on Earth. Since the scale height of N_2 in the Titan thermosphere is large (70–100 km), the maximum ionization occurs in a region of lower total density. Therefore, the $N_2^+(v > 0)$ that are produced will be less efficiently quenched.

The obvious next step is to do the analogous model for Triton, which has an atmosphere of similar composition: N_2 plus hydrocarbons. The interaction of electrons from Neptune's magnetosphere with Triton's atmosphere, however, seems to be more important for producing the observed ionosphere and N_2 emissions [Majeed et al., 1990; Summers and Strobel, 1991; Stevens et al., 1992] than electrons from Saturn's magnetosphere are to the Titan ionosphere and emissions. We will first run a solar model to constrain the amount of electron precipitation that is necessary for producing the ionosphere and powering the dayglow. We will then model the electron energy deposition using an electron transport code developed by H. S. Porter, that we have successfully used to model the Jovian and Venusian auroras.

Table 1. Ionization Potentials

Species	IP (eV)	Reference
N_2	15.58	
CH_4	12.51	
CH_3	9.84	
CH_2	10.40	
CH	10.64	
C_2H	11.0	
C_2H_2	11.41	
C_2H_4	10.50	
HCN	13.59	
HCNH (cis)	6.8	Nesbitt et al. [1991]
HCNH (trans)	7.0	

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JANE LEE FOX

Institute for Terrestrial and Planetary Atmospheres
and Department of Mechanical Engineering
State University of New York at Stony Brook
Stony Brook, NY 11794-2300
(516) 632-8317
FAX (516) 632-8544
(BITNET) JFOX@SBCCMAIL
(INTERNET) JFOX@CCMAIL.SUNYSB.EDU

234 Second Ave.
St. James, NY 11780
(516) 862-8366

Born: [redacted]

Education:

University of Michigan. B.S. in Chemistry with high honors and high distinction, 1973.

William J. Branstrom Freshman Prize. Moses and Sophia Gomberg Scholarships, 1971, 1972. Nola Sauer Minnis Prize. James B. Angell Scholar, 1972, 1973, 1974.

Phi Beta Kappa. Mortar Board (Senior Women's Honorary)

Harvard University. Enrolled September, 1973. Ph. D. in Chemical Physics, November, 1978. National Science Foundation Predoctoral Fellow, 1973–1976. Research Advisor: Professor Alexander Dalgarno.

Employment:

Harvard University. Teaching Fellow, Summer 1974, Fall 1974, Spring 1975, Fall 1975.

Max Planck Institut für Strömungsforschung, Göttingen, FRG. Stipendiatin, Summer 1977.

National Science Foundation National Needs Postdoctoral Fellow, October 1978–October 1979. Postdoctoral Advisor: Professor Michael McElroy.

Center for Earth and Planetary Physics, Harvard University. Research Fellow in Atmospheric Physics, October 1978–January 1980.

University of Illinois, Urbana, IL. Assistant Professor of Chemistry and Electrical Engineering. January, 1980–July, 1981.

Smithsonian Astrophysical Observatory, Cambridge, MA. Physicist. July 1981–August, 1984. July, 1985.

State University of New York at Stony Brook, Stony Brook, NY. Assistant Professor of Atmospheric Sciences and Mechanical Engineering. September 1984–August 1987.

State University of New York at Stony Brook, Stony Brook, NY. Associate Professor of Atmospheric Sciences and Mechanical Engineering. September 1987–December 1991 Associate Professor of Atmospheric Sciences and Marine Sciences January, 1992–present

Professional Activities:

Member: American Geophysical Union. American Astronomical Society, Division of Planetary Sciences.

Associate Editor, Journal of Geophysical Research, Space Physics, Jan. 1989– December, 1992.

Comet Rendezvous/Asteroid Flyby (CRAF) Review Panel. Houston, Feb. 1986.

NASA Planetary Atmospheres Review Panel, July 1989.

Referee for Workshop IX.2 "The Venus Ionosphere" at the biannual meeting of COSPAR (Committee on Space Research) Espoo, Finland, July, 1988.

Co-chairman of "Atmosphere and near space environment of Venus" session at Spring Meeting of the American Geophysical Union, May 1987.

Chairman of "Venus magnetosphere and ionosphere" session at Fall Meeting of American Geophysical Union, San Francisco, Dec. 1989.

Co-organizer (with W. Hoegy) of special session, "Pioneer Venus: Ready for final encounter" held at Spring Meeting of the AGU, Montreal, May, 1992.

Member of the Planetary Atmospheres Management Operations Working Group, 1992–1994.

Co-Convenor (with A. Nagy and D. J. Southwood) of Symposium 3.10 "Planetary Atmospheres and Magnetospheres" at the bi-annual meeting of the International Association of Geomagnetism and Aeronomy to be held in Argentina, August, 1993.

Reviewer of proposals to NASA, NSF, Army Research Office.

Reviewer of manuscripts to J. Geophys. Res., Geophys. Res. Lett., Icarus, Adv. Space Res., Rev. Geophys., J. Phys. Chem.

6 invited review articles (4 published and 2 in preparation)

Publications:

Refereed Journals:

Fox, J. L., A. Dalgarno, and G. A. Victor, The absorption of energetic electrons by argon gas, *Planet. Space Sci., 25*, 71, 1977.

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Fox, J. L., Ar^+ in the terrestrial ionosphere, *J. Geophys. Res., 91*, 1731, 1986.

Fox, J. L., Models for aurora and airglow emissions from other planetary atmospheres, INVITED paper based on presentation at the 1985 IAGA meeting in Prague, *Can. J. Phys. 64*, 1631, 1986.

Fox, J. L., and G. A. Victor, Electron energy deposition in N_2 gas, *Planet. Space Sci., 36*, 329, 1988.

Fox, J. L., Heating efficiencies in the thermosphere of Venus reconsidered, INVITED article for the special issue of Planetary and Space Science in honor of A. Dalgarno on the occasion of his 60th birthday, *Planet. Space Sci., 36*, 37, 1988.

Fox, J. L., and J. H. Black, Photodissociation of CO in the thermosphere of Venus. *Geophys. Res. Lett. 16*, 291, 1989.

Fox, J. L. and A. Dalgarno, Franck-Condon factors and transition probabilities of the second negative band system of O_2^+, *J. Geophys. Res., 1119*, 1990.

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Fox, J. L. and A. I. F. Stewart, The Venus ultraviolet aurora: a soft electron source. *J. Geophys. Res., 96*, 9829, 1991.

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Kim, Y. H., J. L. Fox, and H. A. Porter, H_3^+ in the Jovian ionosphere: densities and vibrational distribution, *J. Geophys. Res., 97*, 6093, 1992.

Fox, J. L., Production and escape of nitrogen atoms from Mars, *J. Geophys. Res., (submitted)*, 1992.

Fox, J. L., The production of hot oxygen at the exobases of the terrestrial planets. *(in preparation)*, 1992.

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Fox, J. L., The chemistry of the Venus nightside ionosphere, INVITED article for the special issue of Planetary and Space Science honoring David Bates on the occasion of his retirement from editorship of the journal. (submitted May, 1992)

Dalgarno, A. and J. L. Fox, Ion chemistry and physics of planetary interest, INVITED review article for *Current Topics in Ion Chemistry and Physics*, (in preparation), 1992.

Refereed book chapters

Fox, J. L., Dissociative recombination in aeronomy, in *Dissociative Recombination: theory, experiment and applications* edited by J. B. A. Mitchell and S. L. Guberman, World Scientific, Singapore, 1989 (INVITED).

Fox, J. L., Airglow and aurora in the atmospheres of Venus and Mars, in *Venus and Mars: Atmospheres, Ionospheres and Solar Wind Interaction (Geophysical Monograph 66)*, ed. J. G. Luhmann, Pepin, and Tatrallay, AGU Press, 1992, p. 191 (INVITED).

Other publications:
"Airglow", (INVITED) entry for *Encyclopedia of Planetary Science*, (submitted, 1992).

Abstracts and presentations at meetings (since 1984):

The vibrational distribution of O_2^+ in the Venusian ionosphere, Bi-annual meeting of COSPAR, Graz, Austria, July, 1984.

Ar^+ in the terrestrial atmosphere, Fall meeting of the American Geophysical Union (AGU), San Francisco, Dec. 1984.

Models for aurora and airglow emissions from other planetary atmospheres, INVITED talk at the 1985 meeting of the International Association of Geomagnetism and Aeronomy (IAGA), Prague, August 1985.

The aurora on Venus, Fall meeting of the AGU, San Francisco, Dec. 1985.

Electron energy deposition in N_2 gas, Fall meeting of the AGU, San Francisco, Dec. 1986.

The aurora on Venus. Presented to the Pioneer Venus Science Steering Group. March 1985, Oct. 1985, April 1986, May 1987, Nov. 1987.

Heating efficiencies on Venus. Presented at meeting of the Pioneer Venus Science Steering Group, Oct. 1986.

Heating efficiencies in the thermosphere of Venus reconsidered, AGU Spring meeting, Baltimore, May 1987.

Particle precipitation and odd nitrogen in the nighttime thermosphere of Venus, AGU fall meeting, San Francisco, Dec. 1987.

Dissociative recombination in aeronomy, INVITED talk at the International Symposium on Dissociative recombination: Theory, Experiment, and Applications, Lake Louise, Canada, May 1988.

Excited states in aeronomy, INVITED talk at the Symposium on Atomic and Molecular Processes, with Application to Aeronomy and Astrophysics in honor of Alexander Dalgarno's 60th birthday, Cambridge MA, June 1988.

The red and green lines of atomic oxygen in the Venus nightglow, Committee on Space Research (COSPAR) plenary meeting, Helsinki, July 1988.

Solar photodissociation of CO in planetary atmospheres, AGU Fall Meeting, San Francisco, Dec. 1988.

The neutral thermospheres of Mars and Venus, INVITED talk presented at the AGU Spring Meeting, Baltimore, May 1989.

G. A. Victor, J. Raymond, and J. L. Fox, Electron energy deposition in oxygen plasmas, DAMOP meeting of the American Physical Society, May, 1989.

A. I. F. Stewart and J. L. Fox, The Venusian aurora, abstract for the biannual meeting of the International Association of Geomagnetism and Aeronomy, Exeter, England, July, 1989.

Production of hot oxygen at the Venus exobase, presented to the Pioneer Venus Science Steering Group, Sept. 1989.

A signature of auroral activity in the nightside ionosphere of Venus, AGU Fall Meeting, San Francisco, Dec. 1989.

Airglow and auroral emission features on Mars and Venus, INVITED talk at the Chapman Conference on the Comparative Study of Venus and Mars: Atmospheres, Ionospheres and Solar Wind Interactions, Lake Balaton, Hungary, June 1990.

S. W. Bougher and J. L. Fox, Comparative thermospheres: Venus and Mars, talk presented by S. W. Bougher at the Chapman Conference on the Comparative Study of Venus and Mars: Atmospheres, Ionospheres and Solar Wind Interactions, Lake Balaton, Hungary, June 1990.

Chemistry of the nightside ionosphere of Venus, presented to the Pioneer Venus Science Steering Group, Sept. 1990.

Chemistry of the nightside ionosphere of Venus, Annual Meeting of the Division of Planetary Sciences, American Astronomical Society, Charlottesville, Oct. 1990.

The production of hot oxygen at the exobases of the terrestrial planets, AGU Fall Meeting, Dec. 1990.

Particle precipitation in the atmospheres of Venus and Mars, INVITED talk presented at the biannual meeting of the International Union of Geodesy and Geophysics, Vienna, August, 1991.

Nitrogen escape from Mars, presented at the Meeting of the Martian Surface and Atmosphere Through Time Program, Boulder, CO, September, 1991.

The reaction $O^+ + CO_2 \rightarrow O_2^+ + CO$ in the Venus ionosphere, presented at the Pioneer Venus Science Steering Group, Ames Research Center, Mountain View, CA, October, 1991.

Heating efficiencies in the thermopshere of Titan, J. L. Fox and R. V. Yelle, Presented at the annual Meeting of the Division of Planetary Sciences of the AAS, Palo Alto, CA, November, 1991.

Dissociative recombination in planetary ionospheres, INVITED presenation at the Second International Symposium on "Dissociative Recombination: Theory, Experiment and Applications" held in St. Jacut, France, May, 1992.

Models of the Venus nightside ionosphere, presented at the Spring Meeting of the American Geophysical Union, Montreal, May, 1992.

Production and escape of nitrogen atoms from Mars, presented at the Workshop on the evolution of the Martian atmosphere, Kona, June 1992.

On H_3^+ density profiles in the Jovian auroral ionosphere, Y. H. Kim and J. L. Fox, Workshop on Time Variable Phenomena in the Jovian Atmosphere, Annapolis, July, 1992.

Other presentations (not complete):

The nitric oxide airglow in the Martian atmosphere, J. L. Fox and A. Dalgarno, Spring Meeting of the American Geophysical Union, May, 1977.

O^{++} in the Venusian ionosphere, J. L. Fox and G. A. Victor, Spring Meeting of the American Geophysical Union, Toronto, May, 1980.

The chemistry of metastables in the Venus ionosphere, International Conference on the Venus Environment, Palo Alto, November, 1981.

A stratospheric chemical instability, invited talk to Joint Gas and Particulate Science Division and Chemical Kinetics Division Colloquium Series of the National Bureau of Standards, January, 1981.

A stratospheric chemical instability, University of Michigan, Spring, 1981 (exact date unknown).

Nitrogen escape from Mars, Second International Conference on Mars, (exact date unknown), 1981?

A stratospheric chemical instability, Washington University, St. Louis, MO, (exact date unknown) 1982.

A stratospheric chemical instability, Goddard Space Flight Center, (exact date unknown) 1982.

The escape of nitrogen from the Martian atmosphere, Center for Astrophysics Atomic and Molecular Physics Division Seminar, Cambridge, MA, February, 1982.

Nitrogen escape from Mars, LPI Planetary volatiles conference, Alexandria, Minnesota, October, 1982.

The O_2^+ vibrational distribution in the terrestrial atmosphere, Fall meeting of the American Geophysical Union, San Francisco, December, 1983.

Vibrational excitation in planetary upper atmospheres, (INVITED) Air Force Geophysics Laboratory, January, 1984.

Vibrational excitation in planetary upper atmospheres, (INVITED) Goddard Space Flight Center, February, 1987.

Vibrational excitation in planetary upper atmospheres, (INVITED) CONOCO lecture series, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, November, 1987.

Heating efficiencies in the thermosphere of Venus, (INVITED) Air Force Geophysics Laboratory, January, 1988.

Vibrational excitation in planetary upper atmospheres, (INVITED) Physical Chemistry seminar, SUNY-Stony Brook, February, 1989.

The nightside ionosphere of Venus, (INVITED) Goddard Space Flight Center, May, 1990.

Heating efficiencies in the thermosphere of Titan, (INVITED) University of California at Berkeley, Space Sciences Laboratory, November, 1991.

Grants:

Studies of the role of metastables and doubly ionized species in the chemical and thermal structures of the Venusian and Martian ionospheres, NASA Pioneer Venus Guest Investigator Grant. To University of Illinois, Dec. 1980–July 1981. To the Smithsonian Astrophysical Observatory, Nov. 1981–April 1982.

Studies of the chemistry of vibrationally and electronically excited species in planetary upper atmospheres, NASA to the Smithsonian Astrophysical Observatory, Oct. 1983–Sept. 1984.

Studies of the aurorally induced emissions on the nightside of Venus, NASA Pioneer Venus Guest Investigator Grant. To the Research Foundation of the State University of New York at Stony Brook (SUNY-Stony Brook), Jan 1985–July 1988.

Studies of the chemistry of vibrationally and electronically excited species in planetary upper atmospheres, NASA Planetary Atmospheres Program, November 1984–January, 1992

Studies of the effects of vibrationally and electronically excited species in planetary upper atmospheres, NSF to the Massachusetts Institute of Technology, Sept. 1987–Oct. 1989.

Studies of the chemistry of the nightside ionosphere of Venus, NASA Pioneer Venus Guest Investigator Grant, July 1988–November 1992.

Exospheric processes and escape of species from the Martian atmosphere. NASA Martian Surface and Atmosphere Through Time Program, Nov. 1990–April, 1993.

Analysis of EUV dayglow spectra for Triton, Titan and Earth, NASA Neptune Data Analysis Program. Joint with Roger Yelle (Arizona). July, 1991-June, 1992.

Excited states in Planetary Aeronomy, NASA Planetary Atmospheres Program, January, 1991–December, 1993 Equipment supplement.

Travel grant from COSPAR to attend the Meeting in Graz, July 1984; SUNY-New Faculty Development Award, 1985; Travel Grant from the American Geophysical Union to attend the IAGA meeting in Prague, August 1985; SUNY Faculty Travel Grant to attend the IAGA meeting in Vancouver, August 1987

Contracts:

Studies of infrared aurorae (AFGL via Subcontract from Utah State University to the Smithsonian Astrophysical Observatory), March 1984–Sept 1985.